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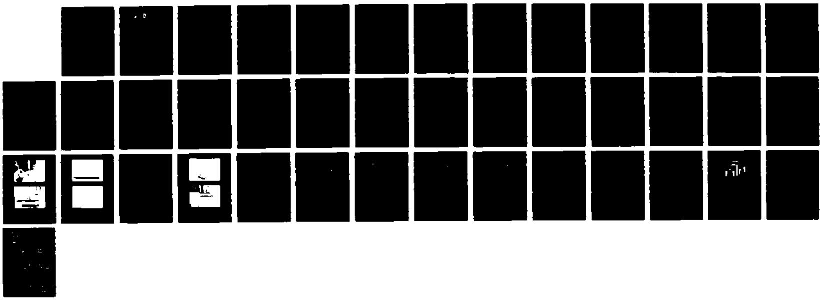

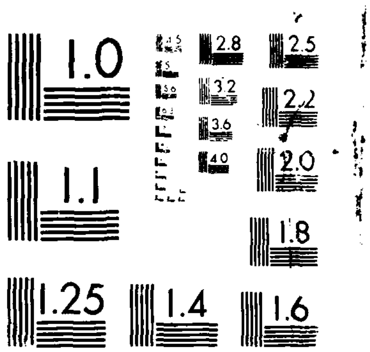

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Measurements of the instantaneous velocity vector are wanted in turbulent flows to determine the three components of mean velocity, the six components of the Reynolds stress tensor, and any higher order components required. It is desirable to obtain these velocity characteristics non-obtrusively, but a combination of the difficulty, complexity, cost and need for optical access and seeding, lead to hot-block anemometry as a complementary approach with different uncertainties and applications. The feasibility of developing hot-block anemometry to measure three-dimensional laminar and turbulent flows was investigated. The design of hot-block probes was addressed and the criteria for the measurement of turbulent flow, which include probe dimensions, power dissipation, probe materials, and sensor configurations, were obtained. Heat-transfer analysis, based partly on combined convection and conduction calculations of two-dimensional geometries, suggest that a three-dimensional probe concept based on hot-film pads is the configuration most likely to meet frequency response requirements for turbulent flows.

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1. Introduction

Hot-block anemometry is a measurement technique for flow velocity based on the principles of thermal losses due to forced convection from a small body, a sphere or block. Temperature or heat-transfer sensors are located to measure variations in the heat transfer rate as a function of position around a hot-block probe. This information is used to obtain the magnitude and direction of local velocity. Figure 1 shows a schematic diagram of a hot-block anemometer with probe instrumentation and data-acquisition system.

The purpose of hot-block anemometers is to measure velocity characteristics of complex, three-dimensional, turbulent or laminar, steady or unsteady flows. The measurement of velocity characteristics in turbulent flow is a problem of great practical importance. Many important flows are three-dimensional and difficult or expensive to measure because of limitations associated with current experimental methods that include impact probes, hot-wires, pulsed-wires, or laser velocimeters. Hot-block anemometry is a novel extension of well-established thermal anemometry to the measurement of instantaneous, three-dimensional flow velocity. Hot-block anemometry would obtain the instantaneous velocity vector, which could be used to provide simultaneous measurements of all three velocity components in time-dependent flows and the three mean velocity components, six Reynolds stresses and any higher correlations required in turbulent flows.

Instruments to measure three components of flow velocity may be divided into conventional methods such as multisensor hot-wires (Ref. 1), three-component laser velocimeters (Ref. 2) and five-hole impact probes (Ref. 3), each with their own limitations, and special-purpose techniques such as directionally sensitive hot-wires (Ref. 4), split-film probes (Refs. 5 and 6), pulsed-wires (Ref. 7), shielded probes (Refs. 8 and 9) and flying hot-wire anemometry (Ref. 10). Hot-block anemometry addresses the need to measure the instantaneous magnitude and direction of velocity simultaneously but without many of the limitations of the above probe-based techniques and at significantly less expense and instrument complexity than laser velocimetry.

Impact Probes have been used to measure mean velocity in three-dimensional flows (Ref. 3) and can be used to obtain a limited amount of turbulence information (Ref. 11). There are, however, large uncertainties in velocity characteristics obtained with pressure probes in time-dependent or highly

turbulent flows. These probes do not respond instantaneously to changes in the flow field and give an averaged indication of flow characteristics: for example, measurements of turbulence quantities are obtained by difference in the turbulence-averaging characteristics of different probe shapes (Ref. 12). Five hole probes of various types (Ref. 13) can measure mean quantities in flows over a limited range of angles less than about 60-70 degrees from the probe axis, and become less accurate with increasing turbulence intensity. Hot-block anemometry was conceived as an extension of the well-established concepts of five-hole probes for measurement of mean and fluctuating velocity components: hot-blocks would measure instantaneous velocity including turbulence quantities; hot-blocks would allow measurements of velocity at flow angles in excess of 90 degrees to the probe axis which exceeds the flow angle limitations associated with five-holed probes; and lastly, hot-block probes would be smaller and be subject to reduced probe interference effects. Impact probes are currently in wide use and could be directly replaced in many applications with hot-blocks to obtain additional turbulence information, with only marginal increase in complexity, calibration effort and cost.

Several probe concepts have been developed to measure one component of velocity and its fluctuations. Directionally sensitive probes (Refs. 4 and 14) make use of single hot-wires with two additional resistance thermometers to sense the hot wake and thus can obtain forward or reversed flow direction. In a similiar fashion, shielded probes use two hot-wires sensors to measure one-dimensional flow through disc-shaped or cylindrical shields (Refs. 8 and 9, respectively). Pulsed-wire anemometry (Refs. 7 and 15) measures the time of flight of a tracer of heated fluid released from an electrically pulsed heater wire to one of two parallel sensing wires. Conventional single hot-wires are sensitive primarily to the normal velocity component and its fluctuations. Flying-hot-wire anemometry (Ref. 10) moves hot-wire probes along a prescribed trajectory to avoid rectification effects associated with stationary hot-wires in turbulent separated flows. Each of the aforementioned techniques has its own limitations and requires multiple probe orientations to obtain the different velocity components. Multiple sensor probes described below, continuous probe rotation (Ref. 16) or simply discrete repositioning, i.e. rotation (Refs. 17 and 18), of the probe have all been used to effect the required orientations and to obtain necessary measurements. In comparison, hot-block anemometry has a major potential advantage, in that it could obtain all

velocity components, their fluctuations, and all cross-component correlations simultaneously, with a single probe and without the need for probe motion or reorientation.

The simultaneous nature of hot-block anemometry would allow accurate measurements of all correlations, including all Reynolds stresses and higher order correlations. For example, the Reynolds shear stresses $\langle v'w' \rangle$ and $\langle u'w' \rangle$, with U in the direction of the probe axis, cannot be measured to an accuracy sufficient for modeling purposes with current approaches, and these quantities could be obtained routinely with significantly less experimental uncertainty using hot-block anemometry.

Multisensor hot-wire probes have been widely used to measure mean and turbulence quantities in three-dimensional flows (Refs. 1 and 19). These probes use several hot-wires, usually three hot-wires, oriented in order to measure different components of velocity. These probes are relatively large: this can limit their application or result in unacceptable spacial averaging in measurements, for example, of certain vortex and boundary layer phenomena. Triple-wire probes have ambiguities in their response (Ref. 20) which are a consequence of the rectification effects associated with forced convection cooling of a cylinder (Ref. 10) which would not be present with hot-blocks. Multisensor probes are subject to restrictive and expensive calibration requirements (Ref. 21), specifically to account for the effects of aerodynamic interference between the probe pintels of adjacent wires on yaw response as a function of pitch angle (Ref. 19). Hot-block probes would have only one support pintel so that this type of interference between sensor supports would be absent. Hot-block probes would be considerably smaller than multisensor hot-wires and, accordingly, spacial-averaging and probe-interference would be reduced.

Heat loss sensors based on a sphere wrapped with a hot-film (omni-directional probe, Ref. 22), a ceramic post with a coated heated platinum wire (Kurz, Ref.23), coated hot-films (Ref. 24), and transistors (Ref. 25) have also been used successfully to measure the magnitude of velocity over a wide range of flow angles but these probes do not obtain flow direction. The first two of these probes, the omni-directional probe (Ref. 22) and the ceramic post probe (Ref. 23) were modified and used in this study as described below.

Split-film probes, which measure heat transfer from two or three sensors on a cylindrical fibre (Refs. 5 and 6), are most similiar to the hot-block

concept. The variation of heat transfer around a cylinder is sensed at locations 180 degrees (two sensors) or 120 degrees (three senso[illegible] apart. The two components of mean and fluctuating velocity in the plane per[illegible]ndicular to the axis of the cylinder are obtained. The current trend is t[illegible] increased use of split-film probes according to manufacturers (Refs. 26 [illegible]7), but their wide spread use has not been adopted, primarily for the following reasons: they are intended primarily for two-dimensional separated flows; one probe can distinguish only two of the three velocity components with associated experimental uncertainties; the technique is not as generally applicable as, for example, non-intrusive laser velocimetry discussed below; and there are also some unresolved difficulties in the interpretation of split-film measurements associated with the cooling effects of the tangential velocity components, W and w' (along the cylinder axis). Hot-block anemometry is not constrained by the two-dimensional limitations of split-film probes and would be applicable to a wider range of practical flow configurations.

Laser anemometry is very attractive by virtue of its non-intrusive, self-calibrating and linear measurement capability, and consequently has been widely used for velocity measurements, primarily with one component velocimeters to date. Two and three component laser velocimeters are now commercially available and, with limitations, can measure two and three components, respectively, of mean and fluctuating velocity component[illegible] and three component systems have had somewhat limited use to date becau[illegible] their expense and their recent introduction to the market. Hot-block anem[illegible]etry represents a complementary alternative to laser velocimetry: hot-b[illegible] anemometry would have different uncertainties and applications. The primary difficulties with laser velocimetry are associated with access, seeding and expense. For example, the location and dimensions of [illegible] volume and the behavior of seed particles may result in unaccep[illegible]certainties in regions of complex surface curvature (Ref. 28) or in [illegible] vortex flows (Ref. 29). Laser velocimetry is expensive be[illegible]n of the sophisticated level of expertise required to [illegible]ents and the cost of models, optical access and instr[illegible]mentatio[illegible] [illegible]robes would be prefered in certain complex geometries [illegible] not possible or would result in unacceptable uncertainty. For e[illegible]mpson et al. (Ref. 28) were required to develop refractive-[illegible]hing techniques using liquids to overcome the problems of complex ge[illegible]ir

representation of gaseous flow in a rocket engine application. To obtain simultaneously three components of mean velocity, as could be obtained with hot-block anemometry, a three component laser velocimeter would be required. Although laser velocimetry has non-intrusive advantages, albeit with some uncertainty associated with particle behavior, hot-block anemometry should be preferred in a number of applications as a much less expensive measurement technique which can provide three components of mean flow, as well as all the components of the Reynolds stress tensor, provided probe interference can be arranged to be unimportant.

The objective of the Phase I study was to establish the feasibility of hot-block anemometry. Emphasis was placed on proof of the concept and on the hot-block probe and its manufacture. The principle of hot-block anemometry is established from the measurements below. Three prototype probes in air flows at velocities up to 130 m/s and at angles in the range from aligned to perpendicular to the probe axis, were used in the Phase I program. Available instrumentation used to operate constant-temperature hot-wires and hot-films (Refs. 30-33) and temperature sensors (Ref. 34) was applied to the Phase I prototype probes. Manufacturing processes based on a variety of existing technologies, for example heat transfer gauges (Ref. 35), split-film probes (Ref. 6), transistors (Ref. 36) and three-dimensional photolithography (Ref. 37), were investigated for application to the three-dimensional probe configurations necessary for hot-block anemometry. A combination of constraints and requirements resulted in the recommendation of a hot-block probe design in Section 7 for development in Phase II. The constraints are associated with current manufacturing technologies that are currently available or viable to develop. The requirements are for adequate frequency response, signal-to-noise ratio, and thermal isolation, which were obtained in the following Phase I experiments and analysis.

The most critical aspect of hot-block anemometry is the hot-block probe and the following section presents probe concepts and discusses the prototype probes investigated in Phase I. Section 3 and 4 describe the instrumentation arranged to test the prototype probes and the Phase I test configuration, respectively. The Phase I experimental and computational results are presented in Sections 4 and 5, respectively, followed in Section 6 by discussion of the implications of these results for hot-block probe design including

manufacturing and material considerations. The report ends with a summary of the more important conclusions.

2. Probe Configurations

The hot-block probe is the critical element in hot-block anemometry and this section presents possible hot-block probe configurations, discusses their advantages and disadvantages, and decribes the Phase I prototype probes. Two hot-block probe concepts were investigated in Phase I to establish the feasibility of their application to turbulent flow problems and they are shown on Figures 2 and 3.

The hot-block probe concept based on hot-film sensors is shown in Fig. 2. Five or more hot-film sensors are mounted on the top and sides of a sphere or block, and are operated as constant temperature anemometers. Heat transfer rate varies with location around a sphere (Ref. 38) and each hot film will have heat removed at a rate dependent on the magnitude and incidence angle of flow velocity on the probe. The combination of heat dissipation rates from the five hot-films can uniquely describe the incident velocity vector. Calibration is needed however to account for variations in probe construction, conduction along electrical leads and any unavoidable interaction between the heated films. Side-flow probes with a single hot-film mounted on the side of the probe (Ref. 39) have been used for the measurement of cross flows in liquids and this concept has similarity to hot-block probes. The frequency response of the hot-films on these side-flow probes can be estimated, using the methods of Ref. 31, to be in excess of 10 Khz, which is acceptable for turbulence measurements but the size of the probe would affect the flow structure. With a single sensor, the side-film probe has a 1.5 mm diameter and a 6.3 mm length and straight forward extension to a probe with multiple sensors would give a probe at least twice as large. This would disturb the turbulence structure of the flow as discussed in Section 7 below and would be unacceptable for the proposed velocity measurements in turbulent flow. Similiar evaluations of current probes (Refs. 25 and 40) suggests new manufacturing methods are necessary for smaller probes and these are discussed in Section 7.

Figure 3 shows the second of the present hot-block probe concepts. This alternative probe is based on a heated core with temperature sensors on the periphery. The rate of heat dissipation from the core would respond to the

magnitude of flow velocity. The temperature sensors would provide flow direction by measuring the distribution of surface temperature on the probe or temperature differences in the probe boundary layer. Temperature could be measured, for example, with micro thermocouples, thermistors (temperature dependent resistors), or transistors (Ref. 28). Calibration would again be required to compensate for variations in probe construction, material imperfections and any non-uniformities in the surface heat transfer associated with the insulating effects of the surface thermometers. Probe construction would be simpler than for the hot-film probe and involve extension of existing probe manufacturing technologies to reduce the size of the probe and to attach or deposit thermistors on the surface. Another important advantage of this second probe concept would be the competitive advantage offered by simpler and less expensive electronics: simple thermistor circuits could be used for the temperature sensors and only one anemometer amplifier and bridge circuit would be required for the heated core. The primary disadvantage is frequency response limitations associated with the necessarily larger thermal mass of the heated core, for the same scale of probe, and this was confirmed in the experimental and calculated results discussed below.

In Phase I, the hot-core probe was used, rather than the hot-film approach, for the following reasons:

1) Either can be used to check basic directional sensitivity requirements. What is true for one is true for the other.
2) Hot-core prototype probes were easier to manufacture. Phase I is a feasibility study.
3) Hot-film time scales are well known. If directional sensitivity was established, these established time scales would allow turbulence measurements, provided adequate size reduction could be achieved.
4) There are questions regarding hot-core time scales. This is discussed further below.

In summary, the hot-core tests are valid for establishing directionality, which is the key to the project.

Three prototype probes were constructed for Phase I evaluation. Prototype 1 is shown in Fig. 4 and is based on a post probe (Kurz 430DC-PC-4) with a ceramic core wound with platinum wire and coated with thermally conductive epoxy to an outside diameter of 1.6 mm. The sensor element is 10 mm long and a thermistor assembly was mounted within 1 mm of the probe tip as shown in

Fig. 4. The thermistor assembly comprised a thermistor bead, imbedded platinum leads, transition leads, and larger gauge connecting wire. The thermistor beads (Thermometrics type BR14KB104K) were 0.014 inch diameter and had a zero-power resistance of 100 and 9 Kohms at 20 and 90 degrees Celcius, respectively. In order to solder to larger gauge wire, the two imbedded 1 inch long lead wires of 0.001 inch diameter platinum alloy were connected to transistion leads of 0.005 inch diameter teflon-insulated stainless steel wire, by spot welding at a power setting of about 1.25 watt-seconds. This welded joint was strengthened with a coating of glue (Permabond 910) and any exposed regions were coated with insulating varnish (GC Red GLPT). These 0.005 inch diameter transition leads were soldered to 38 gauge wire-wrapping wire which could be used to connect to the thermistor circuit described in Section 4. The thermistor assembly was attached to the post probe with adhesive (Permabond 910) which was found to provide adequate strength and minimal thermal insulation. The thermal time constant of the thermistors was about 100 milliseconds in still air and was not measureably affected by attachment to the probe. The completed hot-block prototype probe was delicate, particularly at the joint between the 0.001 inch lead wire and the thermistor, and it was necessary to replace broken thermistors several times during the Phase I effort.

Prototypes 2 and 3 were based on the omni-directional probe (Dantec 55R49) which is a 3 mm diameter quartz sphere covered entirely with a sputtered nickel hot-film and then coated with a 5 micron quartz layer. Three or four thermistor assemblies, prepared as described above, were attached at about the midplane of the sphere to form the probe shown in Fig. 5. (Prototype 3 had three thermistors because only three were available at the time of its construction.) The omni-directional probe was used because of its large dimensions, despite its frequency response limitations associated with a larger thermal mass, to allow multiple sensors to be mounted simultaneously with the objective of identifying flow direction and velocity using a single probe in Phase I.

3. Instrumentation

In Phase I, instrumentation was required to operate the hot cores of the Phase I prototype probes in constant temperature mode, to operate the

surface-mounted thermistors, and to obtain the required voltage measurements. The post probe of Prototype 1 was operated with a special purpose constant temperature anemometer circuit provided by the manufacturer and was adjusted to give a maximum frequency response of about 30 Hz. A general purpose anemometer (Dantec 55M01) with constant temperature bridge (Dantec 55M10) was used to operate Prototypes 2 and 3 with an overheat ratio of 1.4 and an optimized frequency response above 20 Hz. Voltage measurements were made with a digital storage oscilloscope (Tektronics 2430A) and digital voltmeters (Fluke 8050A), as required.

The thermistor circuits shown in Fig. 6, were designed and tested for operation of up to five thermistor beads, simultaneously. The Wheatstone bridge circuit was designed for a null reading at about 90 degrees Celcius, which corresponds to an average overheat temperature of about 70 degrees Celcius for the post probe of Prototype 1 in 20 degrees Celcius room temperature. Resistance values were chosen to allow maximum power dissipation of 15 mW by the thermistor. The bridge adjustment pot was arranged to compensate for differences in thermistor resistances while still allowing the bridge to balance at the one setting of about 90 degrees Celcius. The differential bridge voltage was input to a differential amplifier (JFET input LF353) which was designed with potentiometers that adjust gain and offset. The amplifier was set to unity gain initially and, because the change in thermistor voltage was greater than 10 millivolts in all Phase I tests, it was not adjusted during the Phase I effort.

4. Test Apparatus

The Phase I test apparatus is shown in Fig. 7 with Prototype 1 mounted for testing. A calibration apparatus (TSI 1125) was used to provide a uniform air jet of about 5 mm diameter at known velocities in the range 0.5 to over 100 m/s with low turbulence intensity: for example, turbulence intensity was less than 0.03% at a mean velocity of 5 m/s. The probe traversing mechanism (TSI 1125M) allowed the probe to be inclined up to 90 degrees to the flow direction and was modified to allow 360 degrees of rotation about the probe axis. Inclination and rotational angles were measured within 0.2 and 2 degrees, respectively. Measurements of differential pressure were obtained across the exit orifice of the calibrator and were used to provide jet velocity from an orifice

calibration obtained with the laser velocimeter of Ref. 28. Pressure measurements were obtained with a calibrated strain-gauge transducer (Transmetrics P21BA-131) accurate to within 0.2% of reading for the present range of measurements and this implies an uncertainty less than 2% in the measured velocity values below.

5. Experimental Results

The three prototypes responded to variations in speed and velocity as quantified in the test results below. Preliminary results showed measurable voltage signals could be obtained from the thermistor circuits and anemometer with the prototype probes subject to jet velocities from 0.5 to 130 m/s. Adequate signal to noise ratios, in excess of 10 for all test reports here, were measured and noise is not a factor in the present results and conclusions.

Figure 8 shows the temperature measured by the surface-mounted thermistor on Prototype 1 with the probe axis inclined at various angles to the flow direction. The thermistor is upstream of the probe for negative angles and is directly exposed to flow at ambient temperature. The thermistor measures almost ambient temperature and it is least sensitive to changes in flow direction. Its heat transfer is dominated by conduction from the hot probe and convection to the cold flow which has not yet passed over the probe and been heated. At positive angles, the thermistor is on the leeside of the probe and is exposed to an increasing amount of heated flow in the probe boundary layer and wake. The temperature of the thermistor increases with increasing angle. The largest temperatures are found at low speeds because the rate of heat transfer from the probe and thermistor is less and the thermistor temperature tends to approach that of the hot core. At higher speeds, the thickness of the thermal boundary layer is reduced and, since the amount of the thermistor that protrudes through the probe boundary layer increases with increasing freestream velocity, the average air temperature around the thermistor is less. The results at 130 m/s indicate a decrease in thermistor temperature at positive angles, and this observation was carefully confirmed and found to occur at velocities above about 50 m/s. This effect is likely a consequence of locating the thermistor near the reattachment point of separated flow on the downstream side of the probe tip. This separation region is expected at higher Reynolds numbers and may be associated with laminar-turbulent transition, perhaps as a consequence

of the thermistor itself and associated surface roughness. Increased heat transfer is associated with transition and reattachment and would result in the thermistor being closer to ambient temperature. Further evidence of separation effects are observed in the results at 3 m/s, which indicate a constant temperature above about 40 degrees inclination. This is likely a consequence of a large leeside recirculation which reduces the rate of heat transfer on the back of the probe and results in almost constant values of skin friction, heat transfer rate and surface temperature.

The temperature of the thermistor on Prototype I also depends on the position of the thermistor around the end of the probe. Figure 9 shows results obtained with the thermistor at three positions. In Position 1, the thermistor is upstream of the probe at negative angles and downstream of the probe at positive angles, as was the case for the results of Figure 8. Note the difference in scales between Figs. 8 and 9; the 130 m/sec line of Fig. 8 and the position 1 line of Fig. 9 are identical. In Position 2, the thermistor is always beside the probe and shows the least change in temperature with angle and would be expected. Position 3 is halfway between Positions 1 and 2. The results for the three positions are different as expected, and indicate there is a significant difference in the response depending on both pitch and yaw angle of the probe. These characteristics can be used to obtain flow direction from hot-block probes.

The above results establish the sensitivity of Prototype 1 to the magnitude and direction of velocity and the discussion is changed here to consider the measurement of flow direction with hot-blocks. Figure 10 shows variations of temperature of the thermistor as the probe is rotated with its axis perpendicular to the flow direction for three different flow velocities. The results are appropriately symmetric with a minimum in heat transfer at the upstream stagnation point. The surface temperature distribution is shown to vary with flow velocity on Figs. 10 and 11 and this suggests that calibrations of hot-block probes for flow angle will depend on Reynolds number. It is also clear from Fig. 10 that four thermistors or sensors located 90 degrees apart would uniquely identify flow direction. The need for four thermistors or sensors around the periphery of the probe is confirmed by the results shown on Fig. 12 obtained by rotating Prototype I with the angle of the probe axis inclined at 30 and 45 degrees to the flow direction.

Figure 13 shows the response of the hot post probe and the thermistor to a step change from aligned with the flow direction to an inclination of 20 degrees. The time constant of the post probe and thermistor can be estimated to be about 70 and 180 milliseconds, respectively. This must be greatly improved to obtain useful turbulence measurements as discussed in Sec. 7 below.

Prototypes 2 and 3 were tested at airspeeds of about 10 to 20 m/s. The thermistors measured temperatures on the probe surface which changed depending on the flow direction. With the probe axis aligned with the flow direction, differences between the thermistors was observed to be less than 0.2 degrees Celcuis and were probably associated with slight differences in details of their mounting. At flow angles up to 30 degrees, the hot-film reading which indicates mean velocity was not measurably affected and the surface temperatures indicated by thermistor differed by more than 3 degrees Celcius. These differences in surface temperature could be used to indicate flow direction and this was quantitatively verified with Prototype 1 above. Changes in mean velocity of about 5 m/s affected heat transfer from the hot core of the omni-directional probe appropriately and also affected the distribution of temperature measured on the probe surface. This latter effect suggests Reynolds number dependencies and is likely associated with changes in separated flow on the leeside of the probe. The hot-film of the omni-directional probe was heated with a constant temperature anemometer which keeps the mean probe temperature constant. A temperature distribution on the surface of the probe was expected in a similar manner to that found along hot-wires (Ref. 41). The observation that the temperature distribution changes for different flow speeds at the same angle of incidence suggests that calibrations of hot-block probes may need to account for non-linear effects in speed and angle. The quantitative measurements with Prototype 1 confirm this.

The maximum uncertainty in the values of temperature, angle and velocity are given on Table 1 and are adequate for the purposes of the present discussion and conclusions. Uncertainty also arises due to hand construction of the small Phase I prototype probes and this accounts for some scatter in the above results but again not to the degree that they affect the present conclusions. Probe interference effects in the jet were neglected and may contribute an additional uncertainty less than 1% of velocity magnitude (see Ref. 11). The thermistor was mounted externally on the Phase I prototypes and the glue, thermistor and its leads affect the flow around the probe. It is

difficult to quantify this effect but based on the repeatability of results obtained with different thermistors and lead arrangemants on Prototype I, it seems negligible for the present puposes.

Table 1

Temperature	0.3 degrees Celcius
Velocity	2% of reading
Yaw angle	0.2 degrees
Rotation angle	2 degrees

6. Calculated Results

Calculations were performed with the SRA-developed MINT code, a three-dimensional Navier-Stokes solution procedure, modified to simultaneously solve for conductive heat transfer in the solid and for convective heat transfer in the fluid. A two-dimensional version of the MINT procedure (Ref. 42) was used to solve transport equations for two momentum components, enthalpy, and mass conservation in the solid and fluid regions of the calculation domain shown in Fig. 14. The flow over the probe was assumed to be laminar, since flow over the sensors would need to be laminar in order that signals due to turbulent fluctuations in the flow would not be confused with any generated by the probe: no turbulence modeling approximations were necessary in the calculations.

Boundary conditions for the calculation domain are shown in Fig. 15 and involved sublayer resolution on the solid wall, zero gradient conditions in the freestream flow and in the solid at the flow inlet and outlet, and a specified temperature on the heated wall of the solid. The computational grid spacing was reduced in the fluid near the wall to resolve the steep velocity gradients and to obtain maximum accuracy at minimum computational expense. Constant heat flux could also be specified on the heated wall. Inlet boundary conditions were based on a laminar boundary layer and involved similiarity solutions (Ref. 43) for laminar profile shapes. Static pressure at the domain outlet was reduced to allow air flow through the computational domain and was arranged to give mean velocities over the probe of about 20 m/s. The combination of this velocity, the specified upstream profile, and the dimensions of the calculation domain resulted in a Reynolds number based on distance along the probe surface from the virtual stagnation point upstream of the calculation domain to the sensor, of about Re = 800, which is within the laminar flow regime.

For the limited number of time dependent calculations that were obtained, the temperature of the heated wall was changed over a small number of computational time steps, see Fig. 14, to simulate the conventional square wave tests for frequency response of hot-wire anemometers: it was necessary to change the temperature incrementally over a few time steps for numerical reasons. An overall temperature change of 10 degrees Celcius was used and the time to restabilize the surface temperature was taken as indicative of the probe time constant.

The objective of the calculations was to evaluate the maximum frequency response that might be obtained with hot-block probes. Since a large amount of experimental information is available on hot-film probes and their frequency responses are known to be better than 10 KHz and suitable for turbulence measurements, the emphasis of the calculation effort was placed on the alternative hot-block probe concept with temperature sensors on the periphery of an internally heated block. The specified geometry of the above calculation domain and the aforementioned boundary conditions were used on a 48×168 calculation mesh arranged to represent a simplified version of one thermistor pad on the probe of Fig. 3.

Initial calculations were made with a 100 micron quartz substrate, uniform platinum heater, and an ideal thermistor with zero thermal capacity, and indicated a time constant of more than 0.5 seconds for a device of reasonably practical dimensions. The use of other materials including for example berillium oxide, ceramics, and idealized versions of these materials in combination with the smallest probe dimensions conceivable within current and foreseeable engineering limits, suggested that the maximum possible reduction for the probe time constant is considerably less than two orders of magnitude. To measure turbulence, time constants of the order of 0.05 milliseconds are required and the best possible for the hot-block concept with thermistors and core heating would be more than 5 ms. It was concluded that the proposed concept with thermistors on the surface of a hot core is currently not feasible for measuring turbulent flows, although it might be useful as a robust instrument for other applications. This result is consistent with the above experimental results which indicated that the response time of the ceramic probe and thermistor was about 100 milliseconds. Accordingly, manufacturing possibilities for hot-blocks based on the hot-film concept of Fig. 2 were pursued and are discussed in the following section.

7. Discussion and Probe Design

The computational results above indicate, and measurements confirm, that the hot-block concept with hot-films shown on Fig. 2, should be preferred because it can be arranged to have the least thermal inertia and should provide frequency response suitable for turbulence measurements.

To measure turbulence quantities, sensors must have a frequency that allows resolution of the smallest time scales in the flow. For the majority of turbulent air flows, frequency response of better than 10 KHz would be adequate and this suggest that hot-block probes will need to have minimal thermal capacity. Probes for turbulent flow measurement should have dimensions smaller than the smallest turbulence length scale of importance in the flow and this suggests a hot-block probe must be less than 1 mm in diameter. The major problems in obtaining such a small probe are as follows: the manufacture of 1 mm spheres or blocks; application of hot-film pads less than 0.2 mm in diameter to surfaces of these three-dimensional blocks; the provision of lead wires that connect the hot-films to the probe support and anemometer; and the assembly of probe configurations. Current technology to manufacture side-film probes (Ref. 39), omni-directional probes (Ref. 22), split-film probes (Refs. 5 and 6), and transistor probes (Ref. 25) cannot be extended to the small dimensions required for hot-block probes. The microelectronics industry routinely works with products of the size needed for hot-block probes. Microelectronics technology using photolithography (Ref. 44) can be used to apply leads, and could be used to make hot-film pads, with the required dimensions. It is feasible to extend this technology to apply leads and hot-film pads to three-dimensional blocks (Ref. 45-47). Development of a suitable manufacturing process for hot-block probes is a major part of the proposed Phase II effort and would involve selection and testing of materials, integration of microelectronic and substrate processes, and development of three-dimensional lithography techniques specifically for hot-block probes.

Examination of the needs of hot-block anemometry lead to the probe design shown in Fig. 16 based on the aforementioned microelectronics technology. The most important design criteria for this hot-block probe follow:

1. The probe needs to be the smallest possible for minimal flow interference at the scale of turbulence and should have an overall probe diameter less than 1 mm.

2. Minimal thermal inertia for heat transfer from the hot-film pads and minimal thermal capacity of materials in the probe sensor region are required to provide a frequency response better than 10 KHz. This translates into problems of material selection, minimal sensor mass and process control of manufacturing the probe, hot-film and lead dimensions.

3. The need for adequate sensitivity to flow angle and for adequate signal to noise ratios leads to requirements for hot-film pads that cover less than about 50% of the block face and power dissipation of about 100 milliWatts from each hot-film. This requirement also implies the need for leads that are subject to minimal Joule heating, electrical resistance, and thermal conduction.

4. Minimal interference between sensors results in the need for a substrate material with high electrical and thermal resistance but small thermal capacity. Silicon nitride blocks (Ref. 48) may be acceptable.

5. Each hot-film should be held at a constant temperature and this leads to the need for appropriate hot-film and lead design and for adequate manufacturing controls.

6. There are needs for corrosion protection for the hot-film and electrical isolation from the fluid, especially if it is a conducting liquid. A coating, perhaps beryllium oxide, would serve this purpose and also help keep the hot-film temperature constant as required in item 5.

7. It is preferable to have an aerodynamic shape for the hot block that is, for example, a sphere instead of a cube. Manufacturing technologies limit the shapes that can be applied easily. It would be advantageous from aerodynamic considerations to round the corners of the block shown in Figure 16. Rounded corners may also be advantageous to the process that will plate leads on the corner.

Instrumentation for the hot-block probe of Fig. 16 would comprise five constant temperature anemometers, a data-acquisition system and microprocessor. Calibration and analysis software, for example to obtain ensemble-averaged quantities or to track the velocity vector in real time,

would need to be developed. Hot-block anemometry will require the application of state-of-the-art microprocessor and data-acquisition technology to acquire and analyze the output signals from the multiple hot-film sensors on the probe. Microprocessor-based data-acquisition systems have been used extensively in fluid mechanics research, see Ref. 49 for example, and are directly applicable to hot-block anemometry.

Calibration of hot-block probes will need to vary pitch angle, yaw angle, and flow speed, and would involve slightly more effort than five-hole impact probes and slightly less than multisensor wire probes for equivalent accuracy. Impact probes often do not need to account for effects of flow speed in their angle calibration except for extreme variation in Reynolds number: hot-block likely would. Hot-blocks do not have the aerodynamics interference between the supports for different wires as found with multiwire probes and so less detailed angle calibration is required. Calibration procedures currently used for multiwire probes could be simplified and applied to hot-block anemometry.

Figure 17 shows a second hot-block probe design which is a direct extension of the Phase I prototypes. A robust version of this probe could be produced and, if taken to the limit of current technology, it could have a frequency response less than about 100 Hz, also see Ref. 22, 23 and 50 for evaluation of the individual components. Such a probe would be useful for mean flow measurements but would not be adequate for turbulence measurements. This second probe may have applications in flight testing or weather monitoring and is not recommended for Phase II development. The first hot-block probe concept shown in Figure 16 would have frequency response and dimensions adequate for turbulence measurements and this hot-block probe is recommended for development in Phase II.

8. Conclusions

Hot-block anemometry is a major innovation in flow measurement. The above Phase I results indicate that it can provide measurements currently not possible or subject to unacceptable uncertainty in complex, three-dimensional, turbulent, steady or unsteady flows. The Phase I effort has provided an assessment of the feasibility of hot-block anemometry and the more important conclusions follow:

1. The sensitivity of Phase I prototype hot-block probes to the magnitude and direction of flow velocity was adequate for measurement in three-dimnsional flow fields.

2. A manufacturing technique based on microelectronic technology was found that can be developed to provide three-dimensional probes with hot-film sensors for the purposes of hot-block anemometry. Development of this technology is necessary to obtain a hot-block probe with frequency response adequate for turbulence measurements. The probe configuration of Fig. 16 is recommended for Phase II research and development.

3. Existing instrumentation and microcomputer technology, for example used in flying-wire anemometry, can be applied to the operation of hot-block probes. Special-purpose hardware and software will need to be specifically arranged to obtain and process hot-block signals into useful velocity characteristics.

4. Calibration of hot-block probes will need to vary pitch angle, yaw angle, and flow speed, and would involve slightly more effort than five-hole impact probes and slightly less than multisensor wire probes for equivalent accuracy. A simplified form of calibration procedures for multiwire probes could be developed for application to hot-block anemometry.

5. The hot-block concept based on hot film surface elements shown in Fig. 16 could obtain mean and fluctuating components of velocity at frequencies at least up to 10 Khz. This probe would be a valuable complementary tool for measurement of complex three-dimensional flows. Since hot-block anemometry would require considerably less capital investment and training of personnel than an LV system and it could obtain all Reynolds shear stress components simultaneously and with improved accuracy, it would play a valuable role in experimental fluid mechanics research.

6. The hot-block concept based on surface temperature sensors and shown in Fig. 17, could obtain three components of velocity fluctuations at frequencies less than about 100 Hz with some development of current technology. The probe would be robust and would be suitable as a mean flow device, for example as a

yaw and pitch indicator for flight applications or a wind direction and speed instrument for meteorological or wind-shear measurements.

ACKNOWLEDGMENTS

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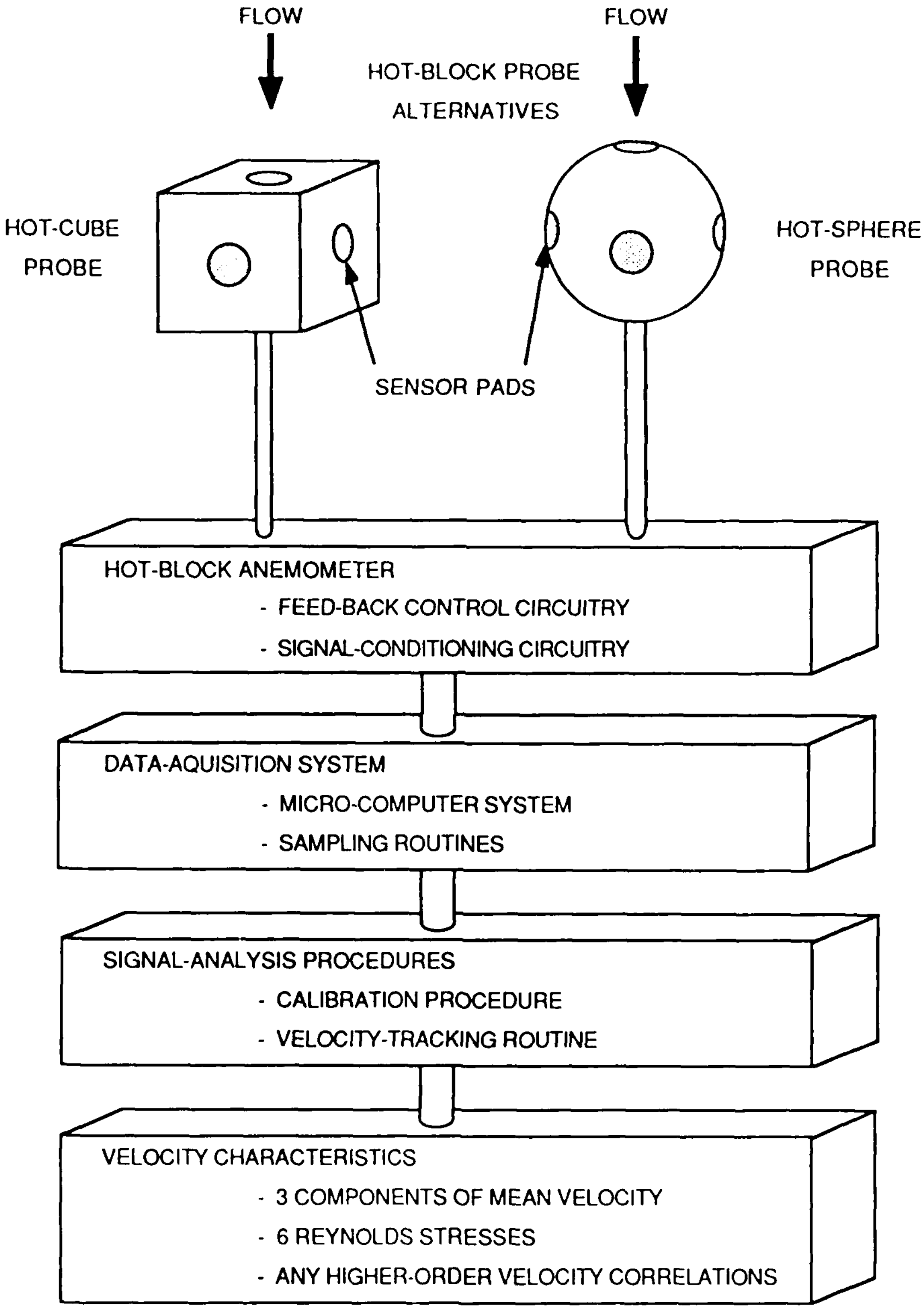


Figure 1. Schematic Diagram of a Hot-Block Anemometer.

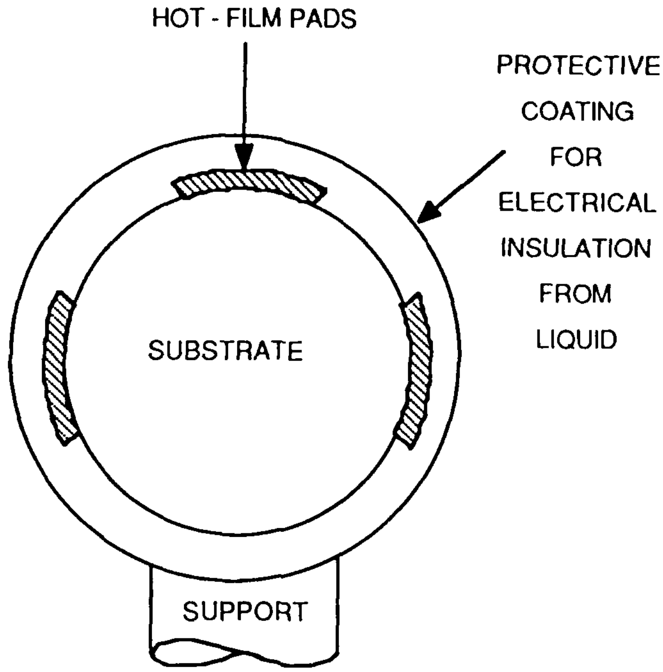


Figure 2. Hot-Block Probe with Hot-Film Pads.

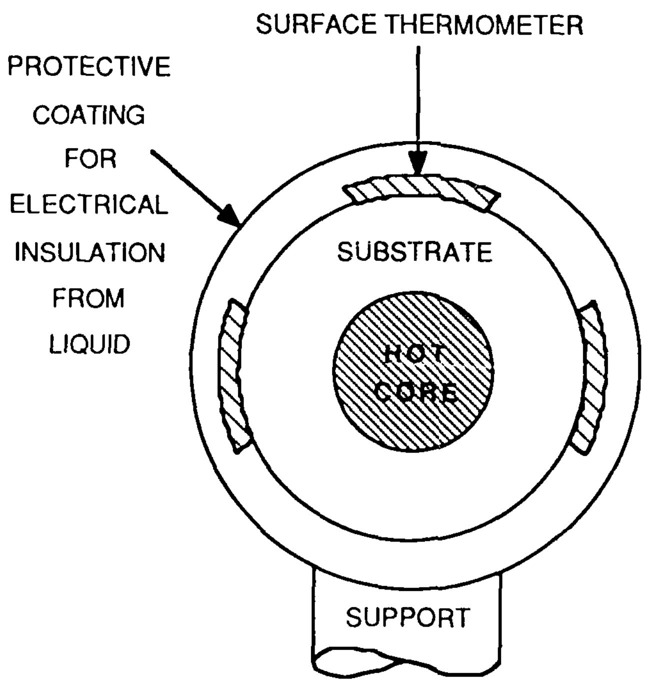
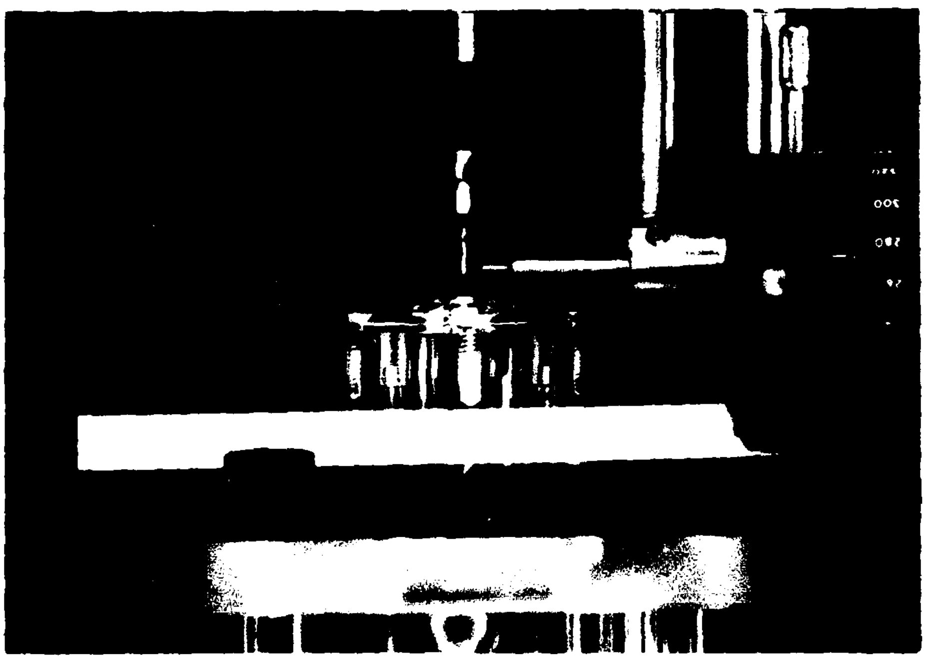


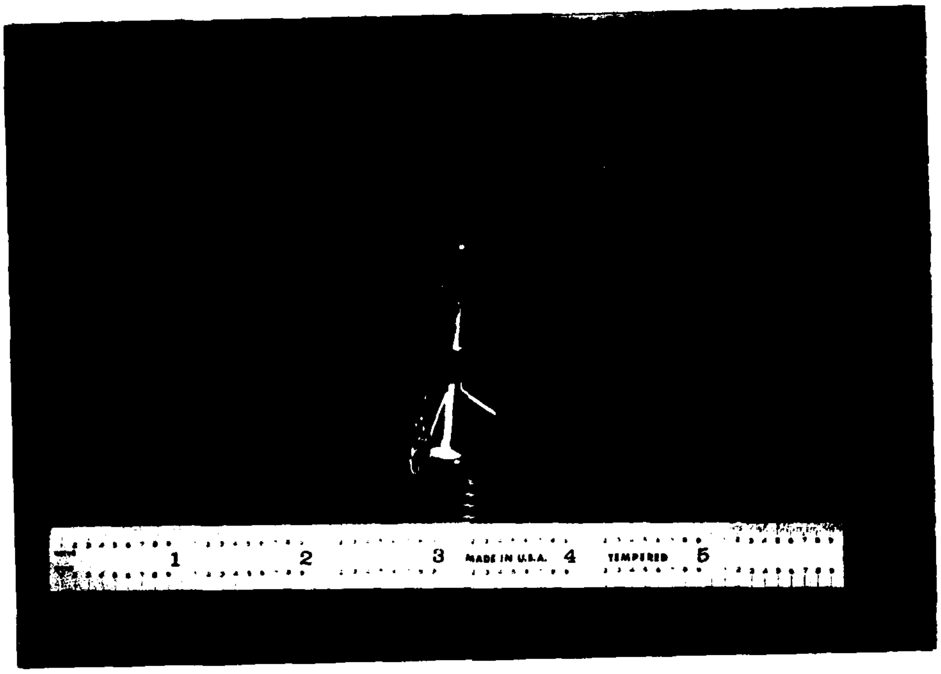
Figure 3. Hot-Block Probe with Surface Thermometers.

a) Prototype 1.



b) Prototype 1 in Jet Flow.

Figure 4. Hot-Block Prototype 1.



a) Prototype 2 with four thermistors.

b) Prototype 3 with three thermistors.

Figure 5. Het-Block Prototypes 2 and 3.

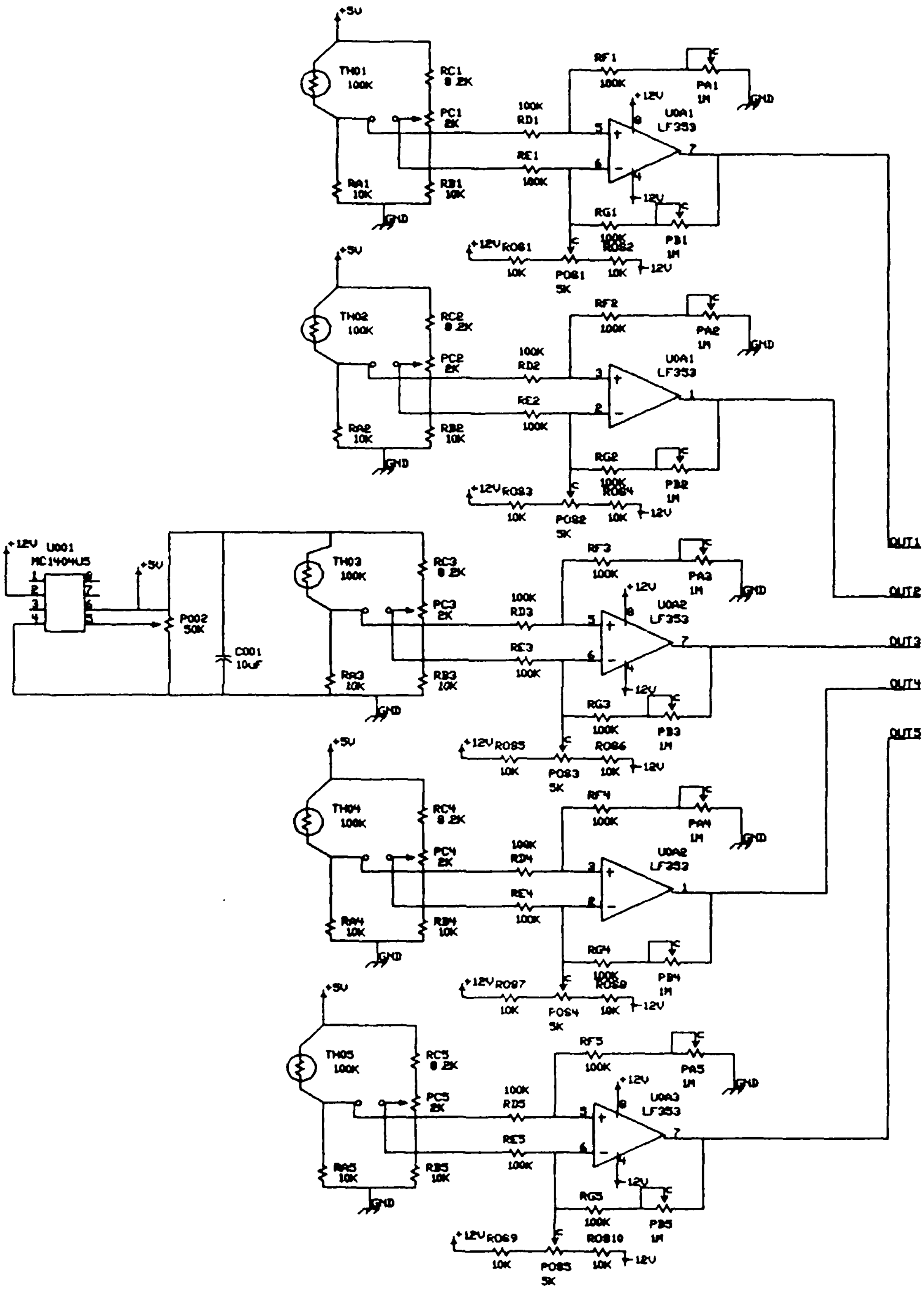
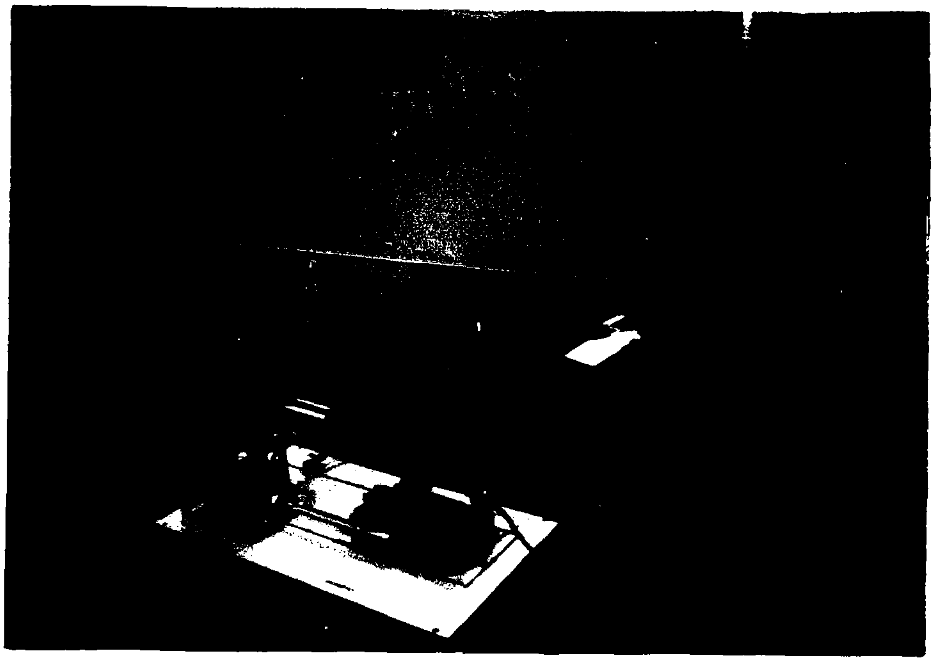
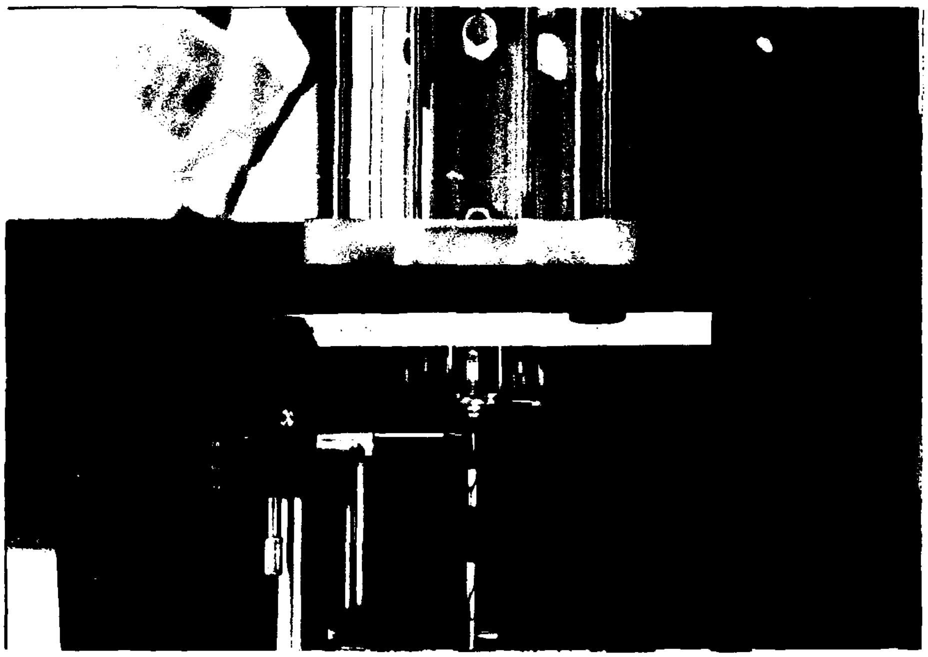


Figure 6. Thermistor Circuit Diagram.



a) Overview.



b) Traversing Mechanism and Jet.

Figure 7. Test Apparatus.

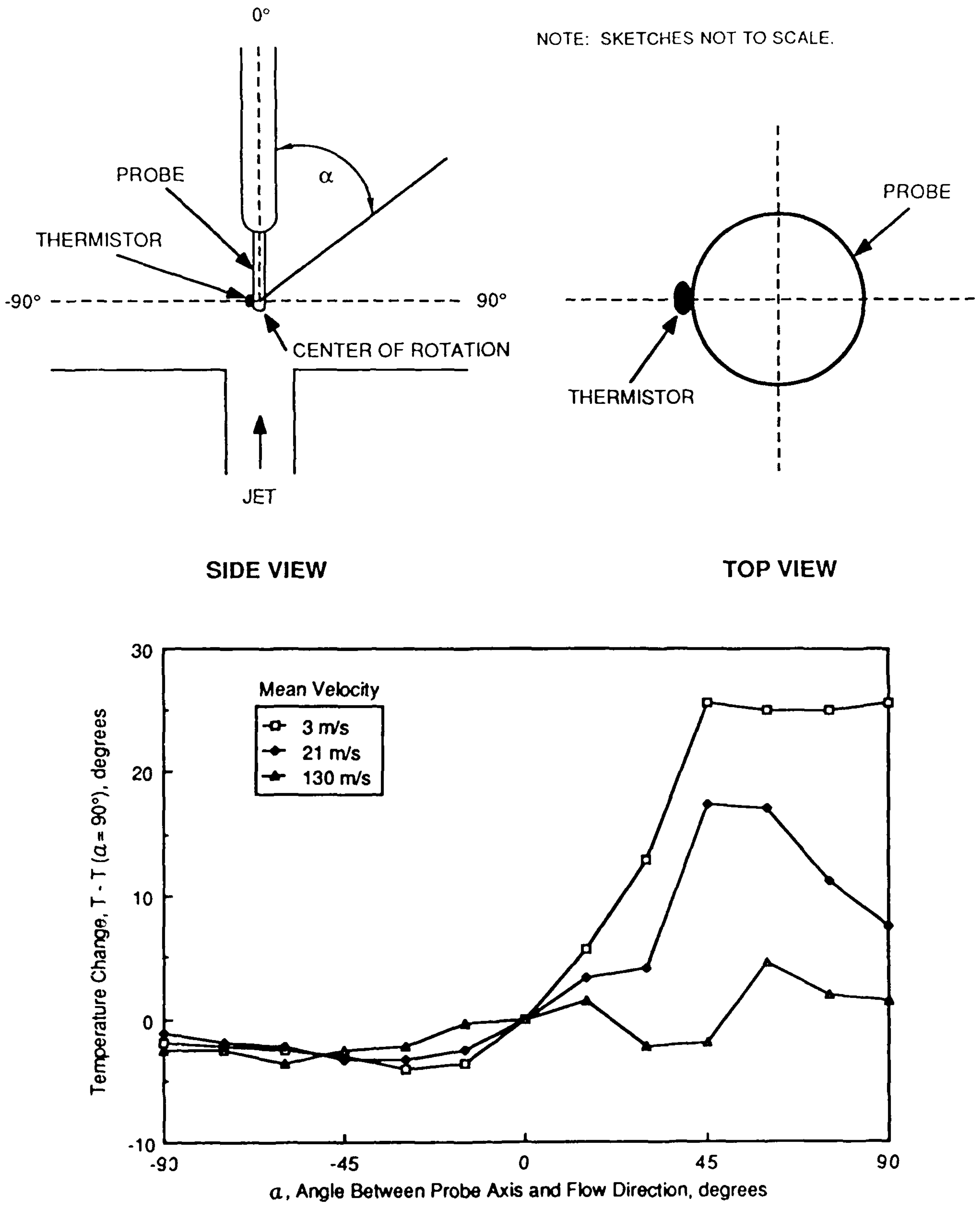


Figure 8. Change in Surface Temperature with Angle Between the Probe Axis and Flow Direction.

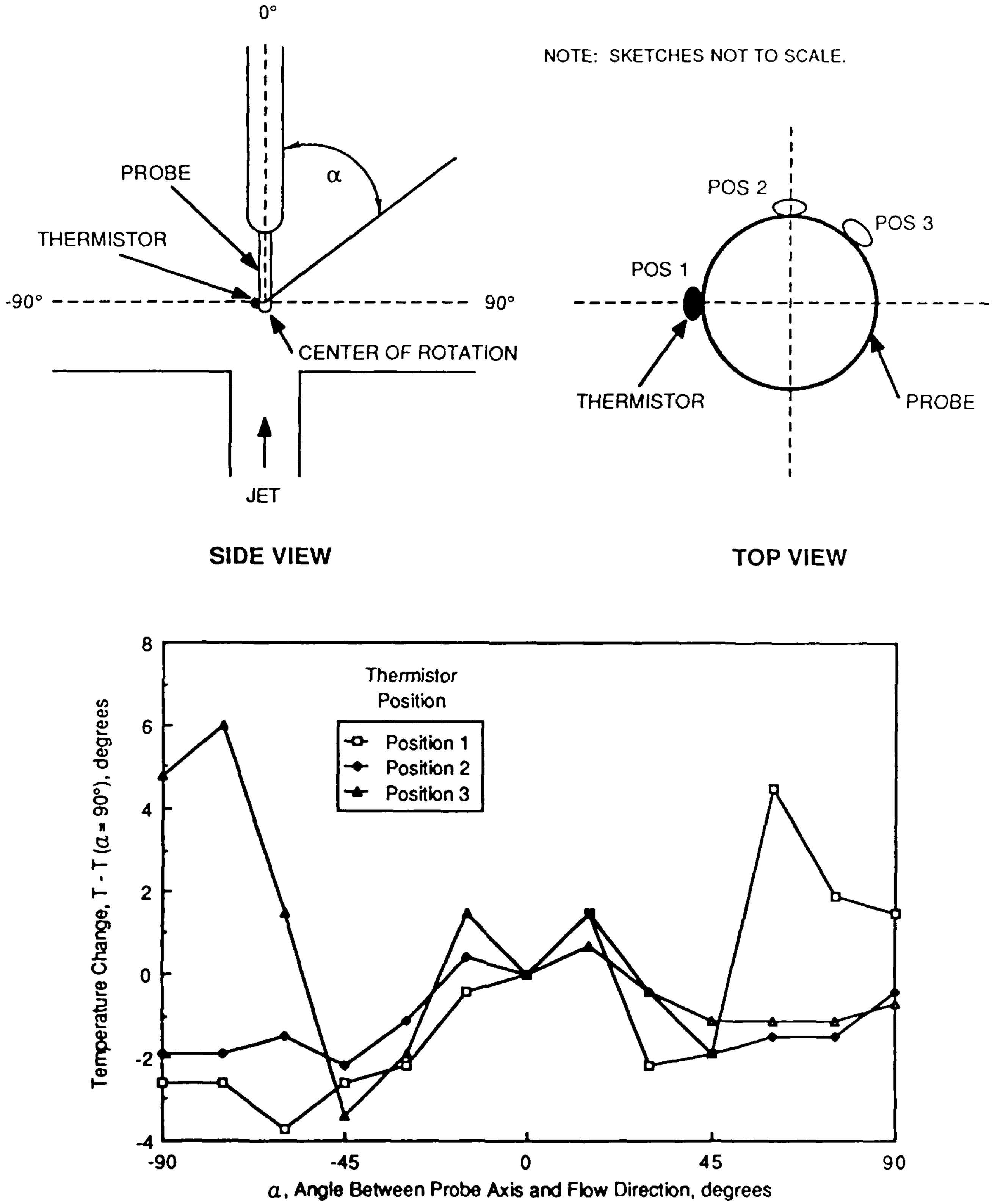


Figure 9. Change in Surface Temperature with Angle Between the Probe Axis and Flow Direction at 130 m/s.

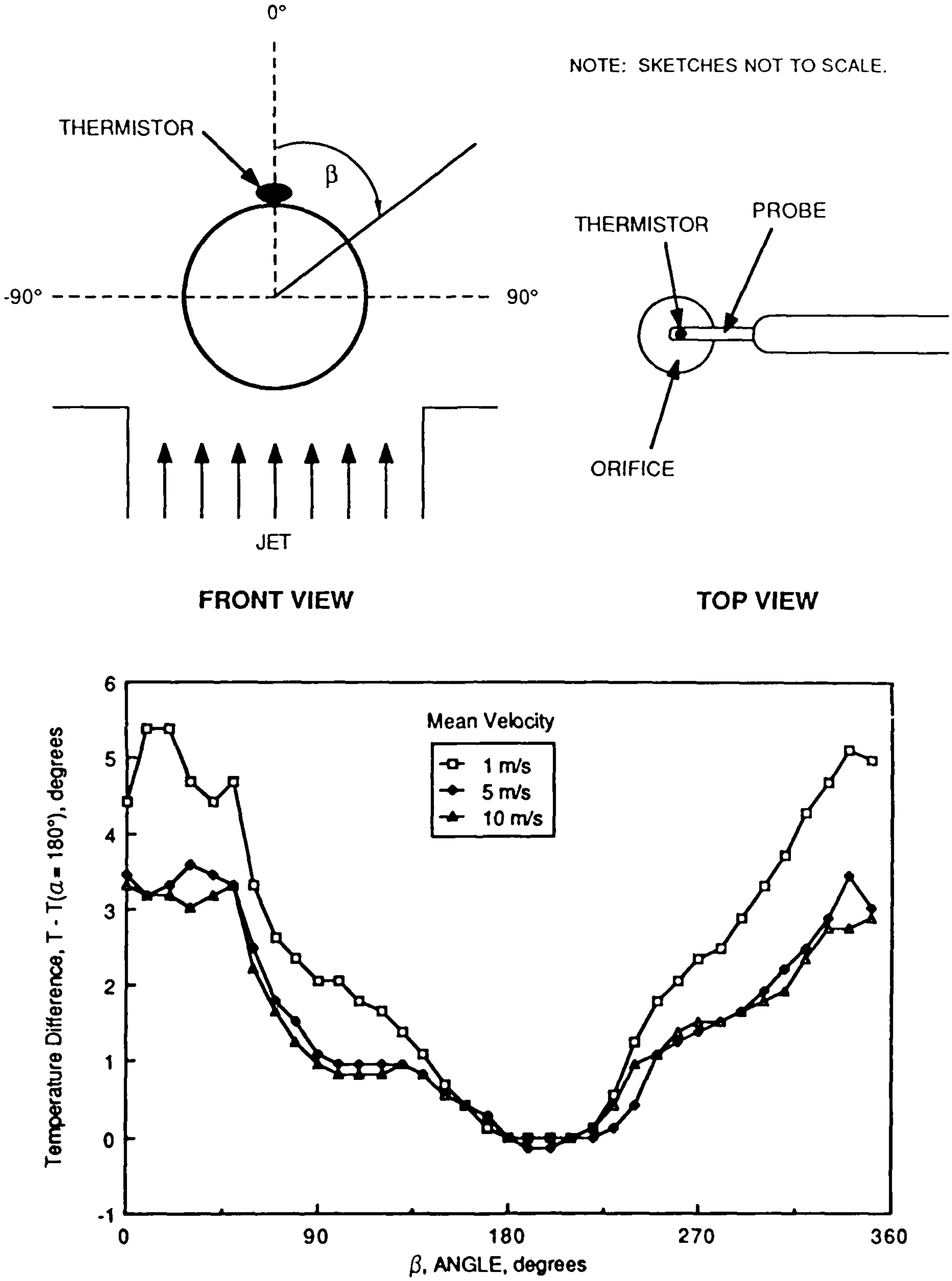
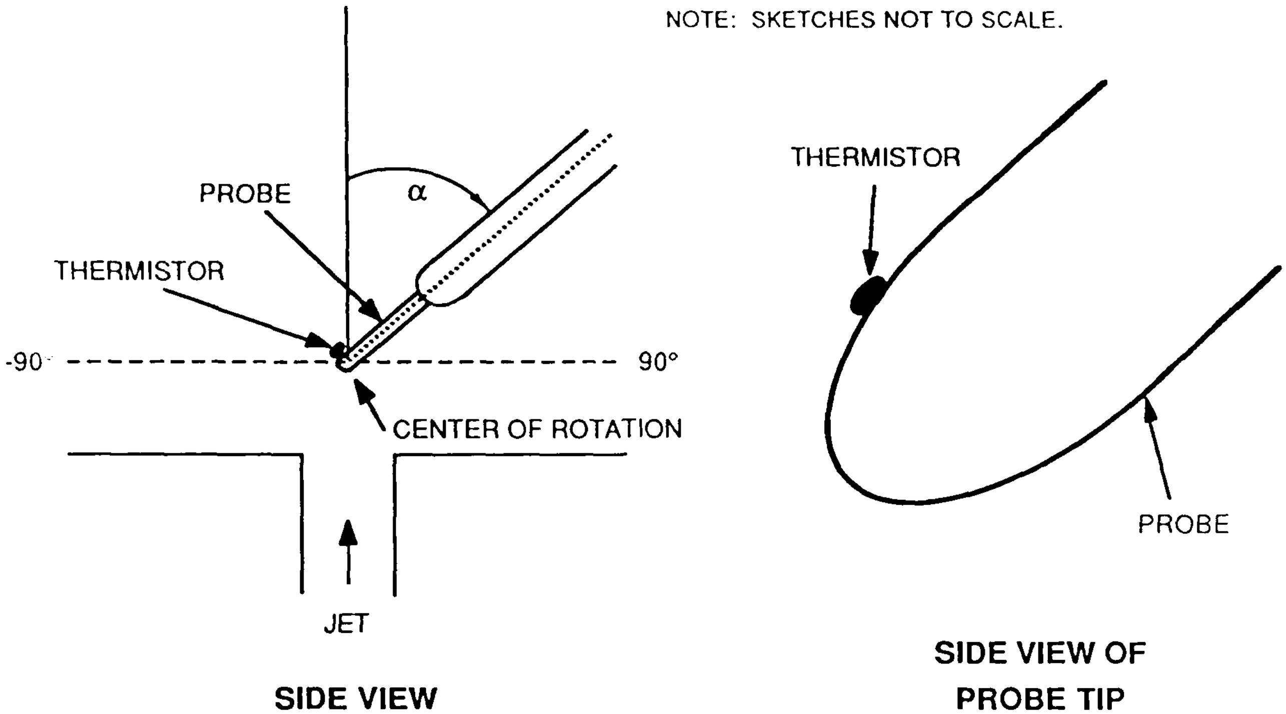


Figure 10. Temperature Difference versus Angle of Rotation with the Probe Axis Perpendicular to the Flow.



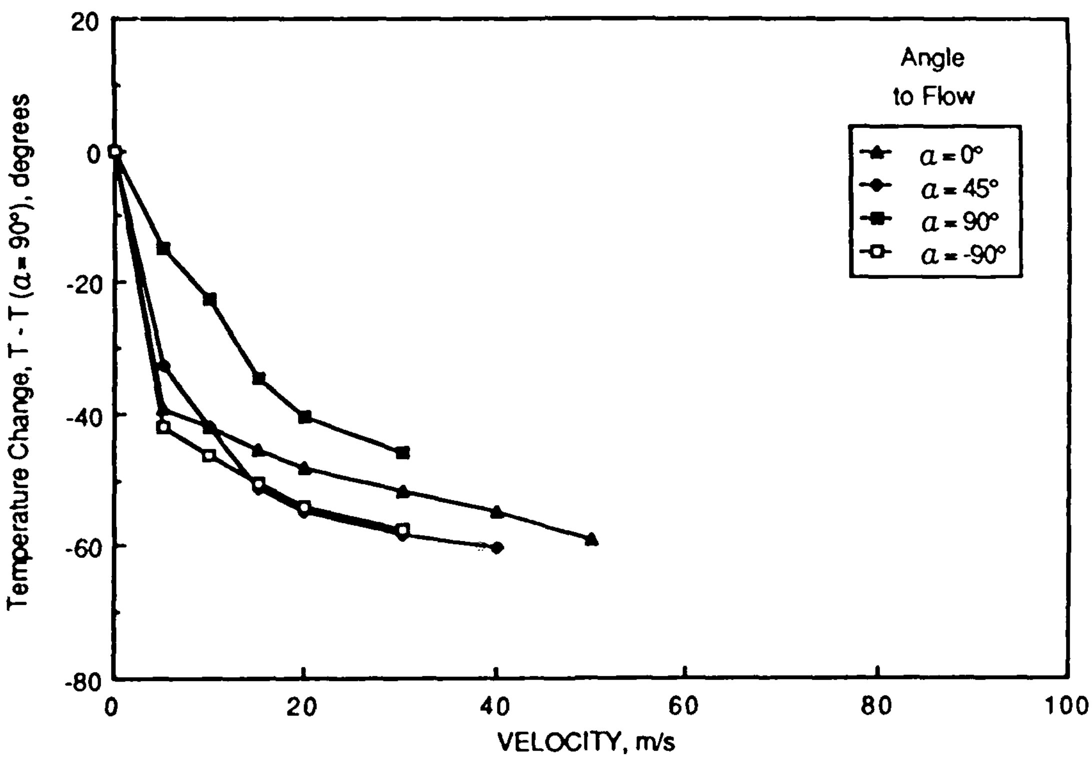
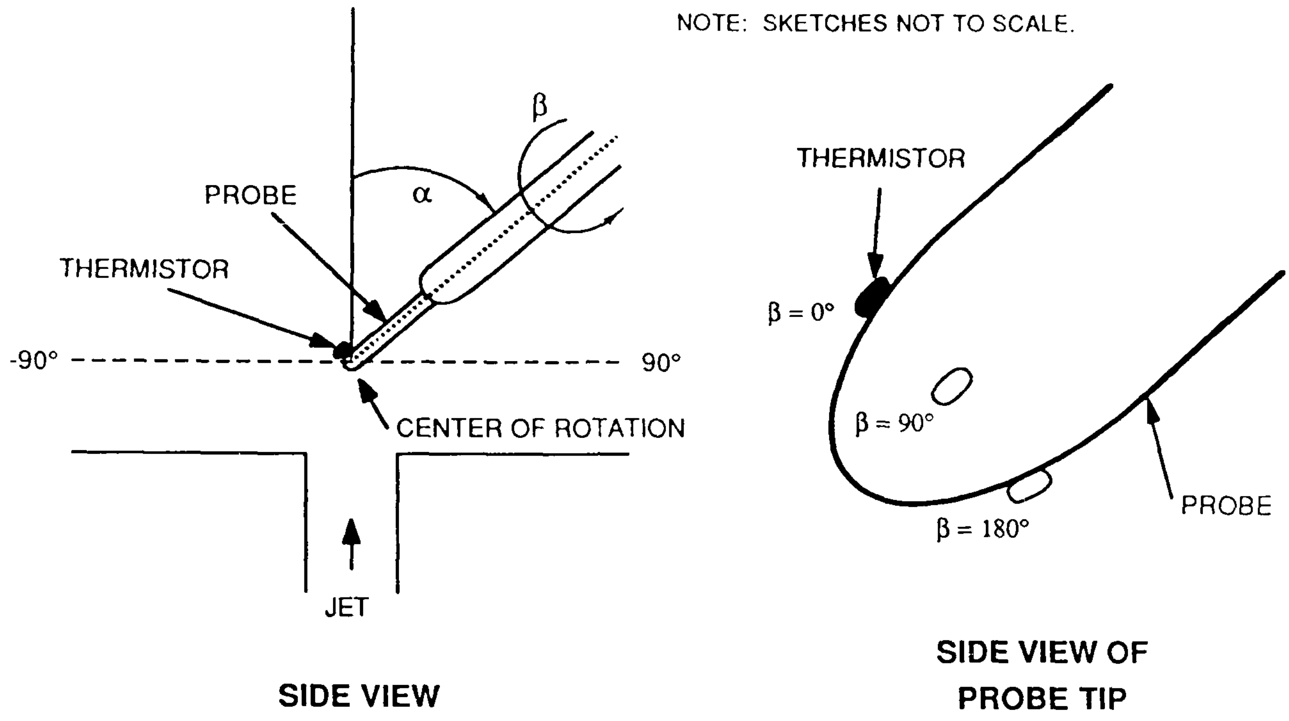


Figure 11. Change in Thermistor Temperature with Velocity.

NOTE: SKETCHES NOT TO SCALE.



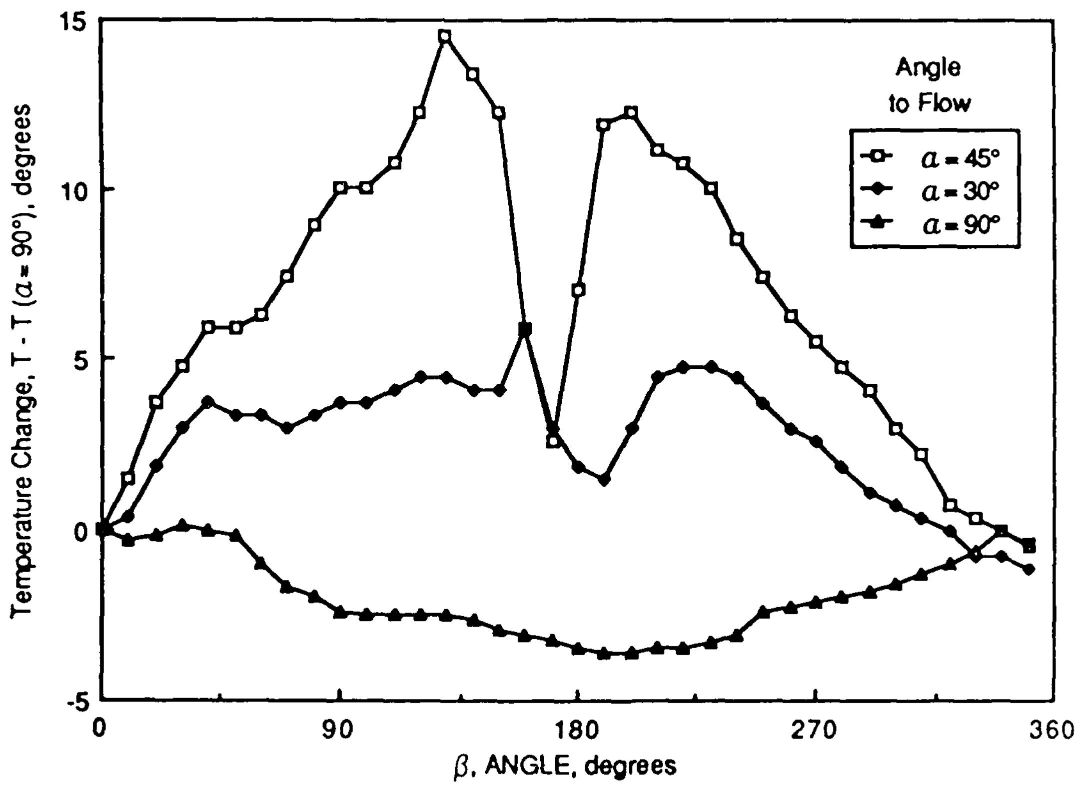


Figure 12. Change in Surface Temperature with Angle of Rotation at 5 m/s.

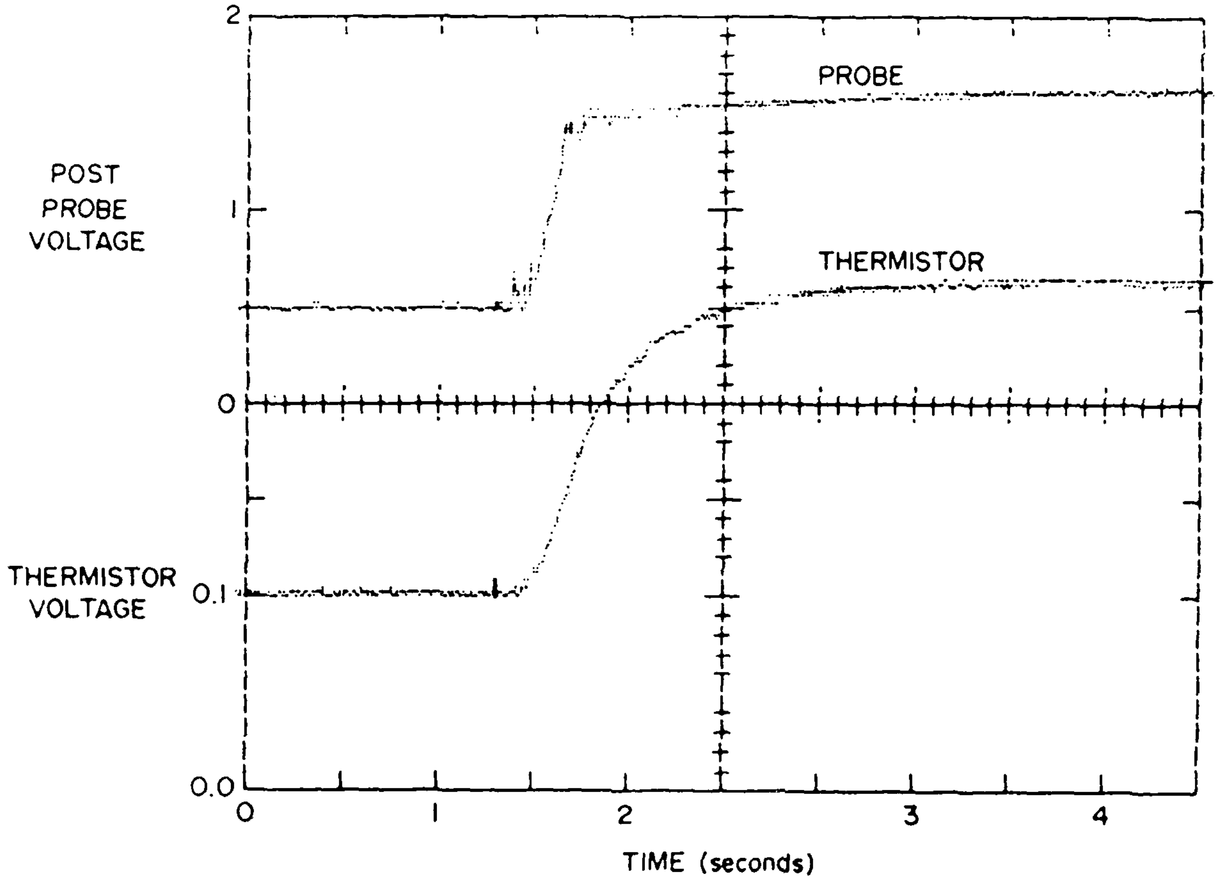
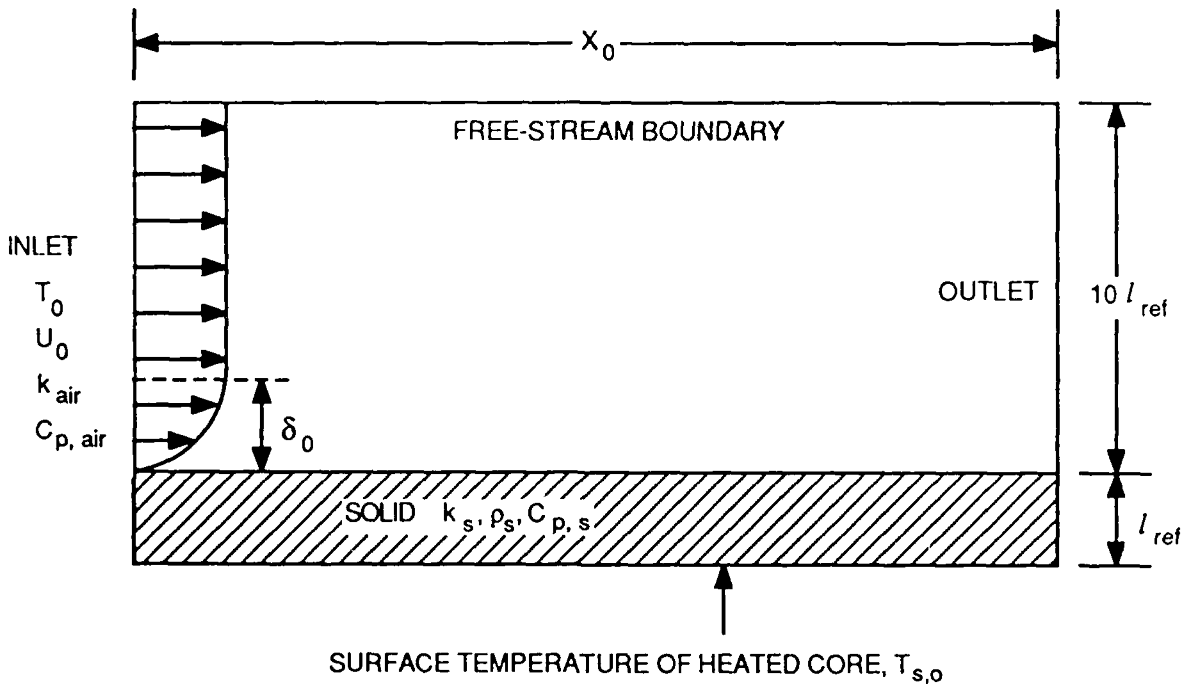


Figure 13. Response to a Step Change in Flow Angle from 0 to 20 Degree Inclination to the Flow Direction.



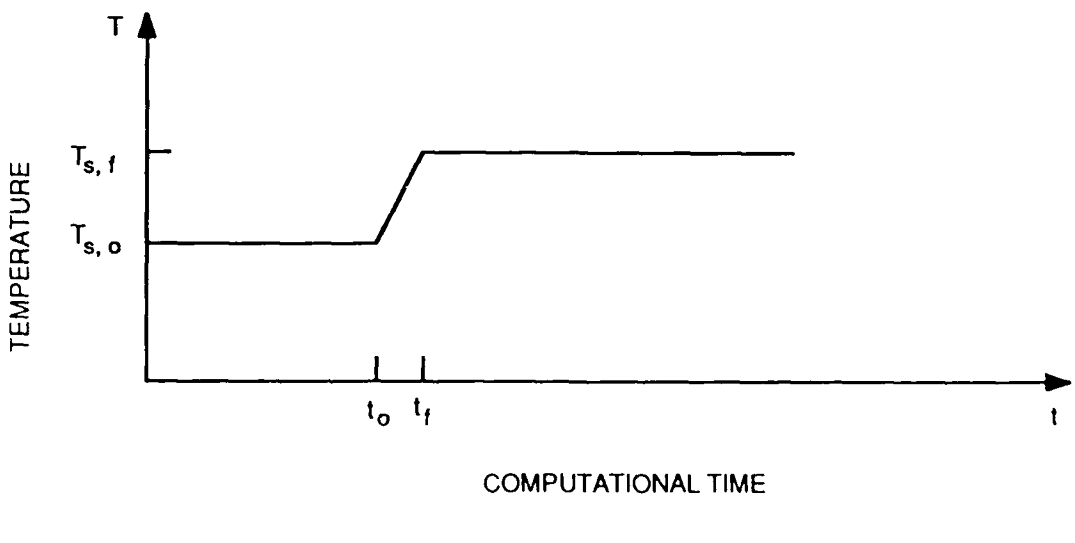


Figure 14. Calculation Domain.

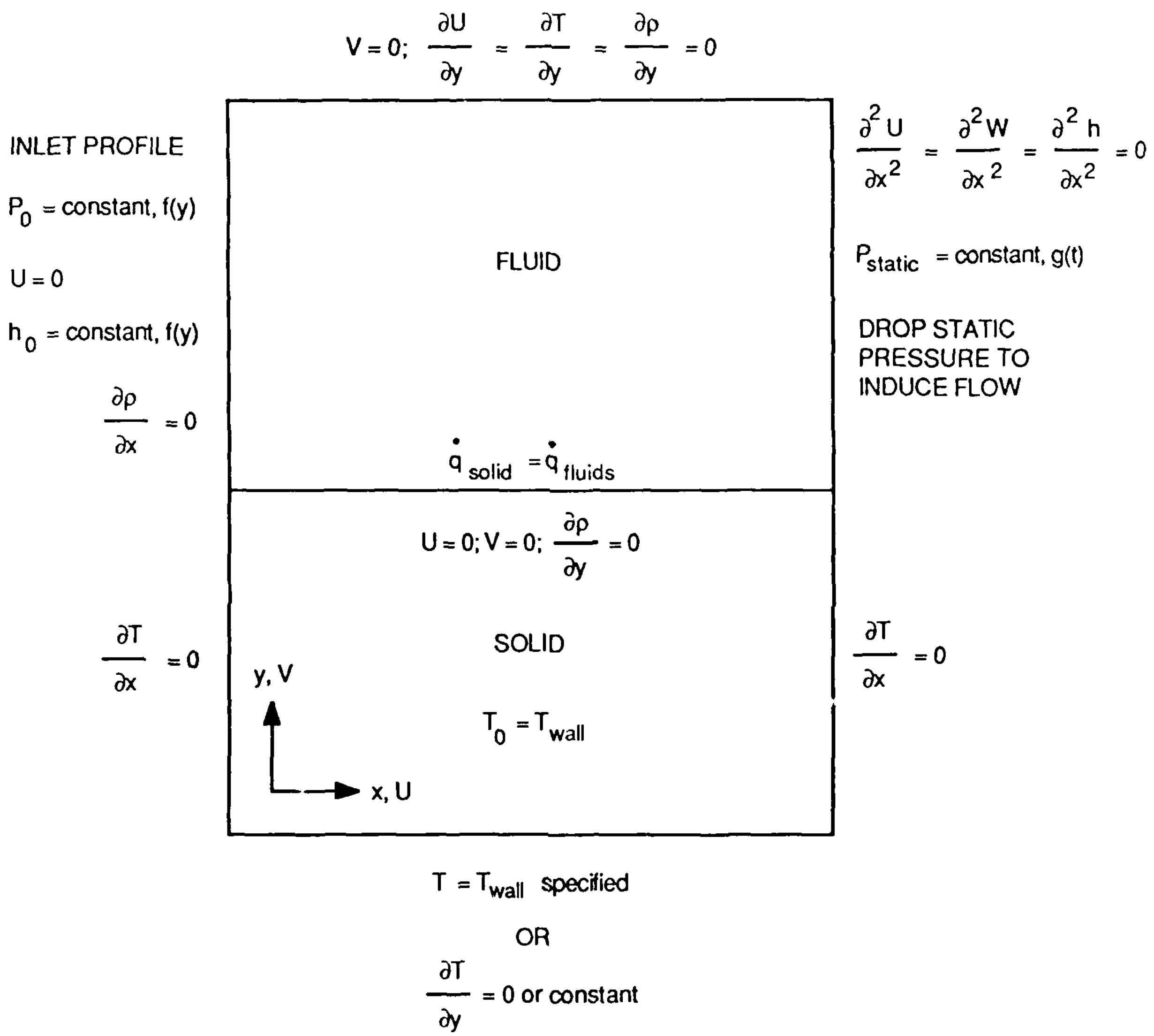


Figure 15. Boundary Conditions.

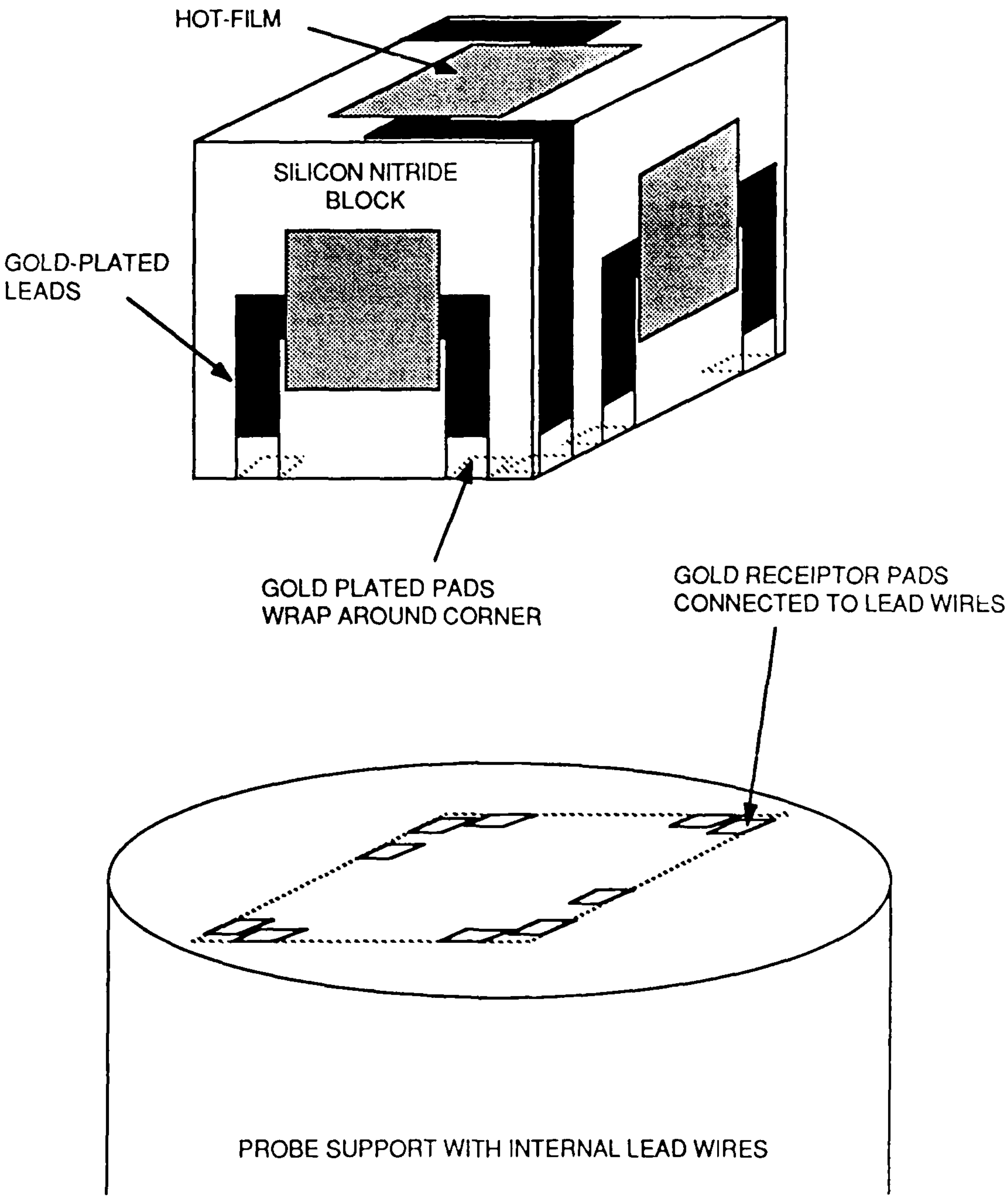


Figure 16. Hot-Block Probe Design based on Hot-Films.

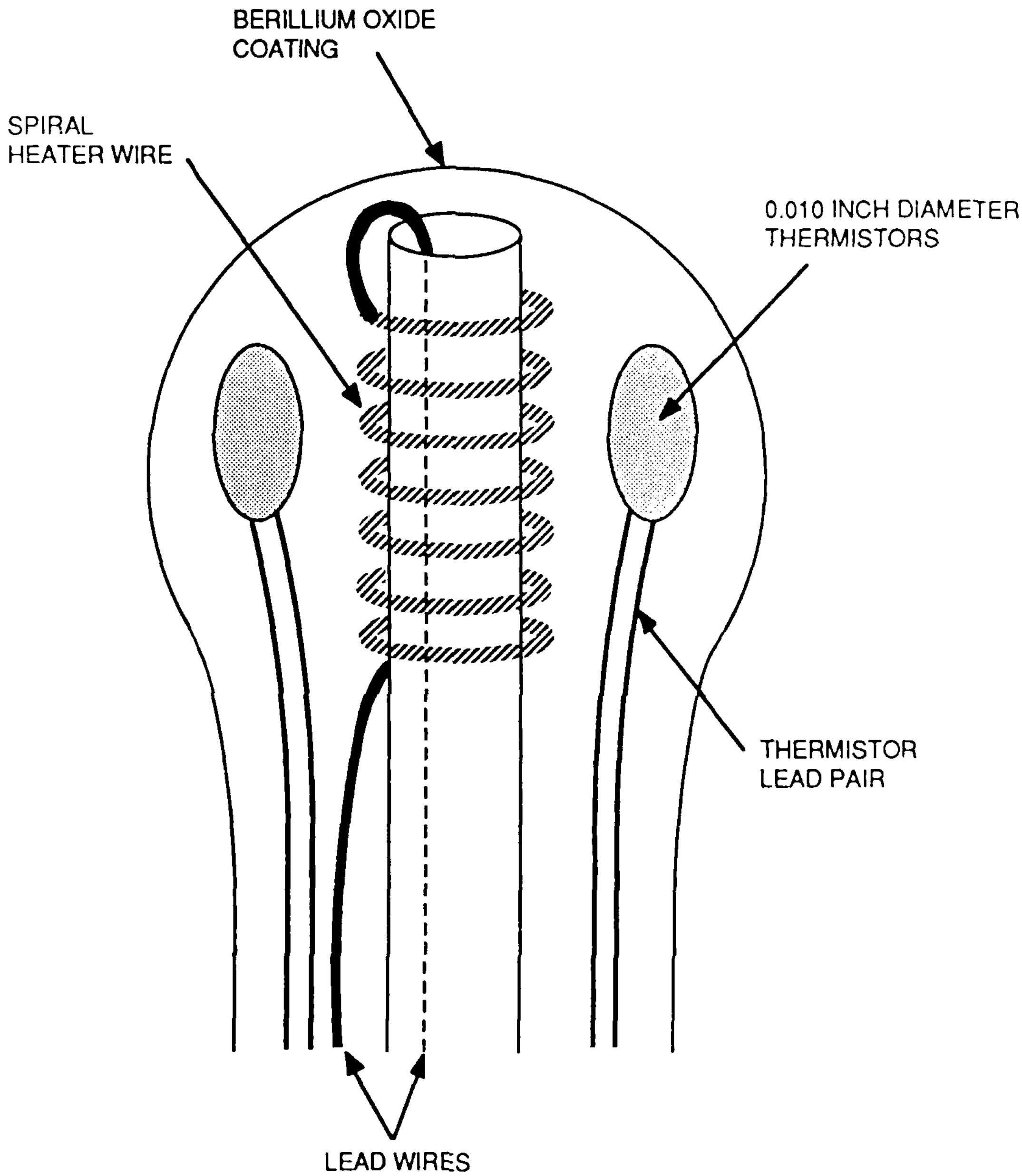


Figure 17. Hot-Block Probe Design with Thermistors.

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